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Contact and frictional properties of stratum corneum of human skin

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Abstract

Most skin tribology studies gave attention on the examination of frictional properties of normal and healthy skin surfaces. This study aims to investigate the frictional and mechanical properties of skin under different load and friction conditions after removing the stratum corneum from the designated uninjured forearm tissue by a tape stripping method. The influence of water on friction coefficient was explained by using adhesion model of friction. For quantifying the amount of removed stratum corneum from the skin surfaces, an UV/vis spectrum analysis was used to measure the absorbance and pseudo-absorbance of stratum corneum on the tape. To evaluate the influence of water on friction coefficient, trans-epidermal water loss (TEWL) value of different skin conditions was assessed by water evaporation measurements. Frictional and mechanical properties of the skin surfaces were acquired via a tribometer. Results revealed that the elastic modulus of skin decreased and the friction coefficient of skin increased with the increasing of the amount of removed stratum corneum. Friction force versus normal force was presented to explain the influence of water on friction coefficient and section change phenomenon of friction coefficient under different degrees of tape strips.

Keywords: Skin friction; Stratum corneum; Tape stripping; Trans-epidermal water loss

1. Introduction

Skin tribology plays an important role because human skin rubs against other external surfaces in our daily life, such as holding a ball [1], using skin care products [2], or touching a finger pad [3]. The comfort experience during the use of these products is closely related to the contact and friction behavior between human skin and product surfaces. The reciprocating sliding and contact between skin and working implements, sports appliances, improper footgear, and textile materials, etc., may lead to skin damage [2]. Therefore, a good understanding of skin tribology is important in the design of human–product interfaces that have tribological functionality and that are comfortable in use.

Skin is composed of three layers – epidermis, dermis and subcutaneous fat with anisotropic mechanical properties. The mechanical properties of epidermis are determined by stratum corneum, which is most external skin layer. Tape stripping is widely applied to dermatologically and pharmacologically study skin layers. The factors that influence the properties of the stratum corneum in tape stripping measurements are thicknesses of the stratum corneum [4], number of cell layers, cohesion between the cells [5,6], and tape stripping conditions (such as the number of tape removals [7], the profile and duration of the force press on the skin [8], indentation depth [9], evaluating facial cleanser [10], and type of tape used [11,12]). Quantitative studies for practical conditions have been conducted [13–15] on the mechanical and frictional behavior of human skin. Not only the type of skin (hard and soft, age [16], gender [17]) and skin conditions (e.g., hydration state, sweat, sebum level) [18] affect skin properties, in addition, the hydrophilic/hydrophobic interface between human skin and contacting surfaces also affects skin frictional properties [19,20]. Research on grip and tactile sensation of

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human skin on friction has increased due to the popularity of touch interfaces and mobile devices [21]. Various factors that influence the friction behavior of human skin have been discussed by a tribometer, such as sliding speed [22] and materials of rotating disc and probe [23,24].

Forearm skin is representative of non-glabrous skin and has low hair fiber density, thus the frictional properties of forearm skin with a smooth surface have been commonly reported. This study evaluated the mechanical and tribological characteristics of tape-stripped forearm skin. Pailler-Mattei et al. [9,25] also studied skin tribological behavior in vivo after the tape stripping procedure. However, the measuring method of stratum corneum removed from the forearm is different. In Refs. [9,25], tapes were weighted before and after the stripping procedure in order to measure the amount of SC removed. However, the weight of tape is determined not only by the corneocyte aggregates, but also sebum, lipids, and sweat [8]. Since corneocyte aggregates represent the basic of stratum corneum on a stripped tape, this study applies the method of combining tape stripping and spectroscopy proposed by Weigmann et al. [8] to measure the mass of the corneocyte aggregates on the tape. Refs. [9,25] showed the importance of the electric charges on skin biotribological behavior. Electric shear strength was added to friction adhesion component. Thus, a physical model was derived to evaluate the friction electric force. The electric shear strength values to calculate the skin friction coefficient after the tape stripping. To quantify the mass of stratum corneum removed from the skin surface and to evaluate the influence of water on friction coefficient, an ultraviolet/visible (UV/vis) spectrometer was used to measure the protein absorption with the decreases of the amount of stratum corneum and the trans-epidermal water loss (TEWL) of each tape strip. Several factors can influence the quantity of stratum corneum that is removed by a piece of tape. In this study, we focus various tape-striping skin by coupling changing probe sliding velocity and normal load, which are not discussed in [9,25]. Eventually, friction force versus normal force was presented by using the adhesion model of friction to explain the influence of water on friction coefficient and section change phenomenon of friction coefficient.

2. Experimental setup

2.1. Skin samples

In the experiment, the skin sample was chosen from the inner forearm skin of a healthy 26-year-old man. The skin sample was not treated with any chemical/cosmetic substances in the 24 h before the experiment and not exfoliated in the month before testing to retain its natural conditions. Before each test, the skin was preconditioned and was washed with water to remove impurities and dried at room temperature (22–24 °C) with a relative humidity of 45–55% for approximately 30 min. Notably, sebum existed on skin surface, if the skin washed with water. Sebum on lipidic film affected the skin adhesion behavior due to capillary phenomena reported in [9,25], and should be further investigated. The friction tests were carried out on the inner forearm, at 5 cm from the wrist. Before the procedures and measurements of the studies began, the volunteers rested for acclimatization for at least 30 min in the test room. Informed consent was obtained, and this study was approved by the ethics committee of the National Cheng Kung University. It is well-known that friction measurements could vary from one human to another. The tests were carried out only on one volunteer, which was not conducive to statistical analysis of data. However, to compare the general frictional performance of the different agent–surface combinations under the various test conditions, using one subject would be appropriate.

2.2. Tape stripping

Commercially available adhesive tape was utilized in this study (DEER BRAND®, Symbio Inc., Taiwan). The tape consisted of biaxially oriented polypropylene and a solvent-based acrylic adhesive. The adhesive film had a length of 30 mm and a width of 19 mm. The tape was applied to the identical skin area and pressed for 10 s before peeling off from the skin in a fixed direction. The peeling speed was of 20 mm/s. Tape samples were collected after every 5th, 10th, 15th, and 20th times stripped, respectively, for the following experiments.

2.3. Indentation and friction tests

Indentation and friction tests were carried out by a nano/micro-tribometer (UMT-2, Bruker) (Fig. 1 left). Indentation test was applied to measure the normal stiffness of forearm skin. During the indentation (loading/unloading) process, the applied normal load F_z was increased from 0 to 196 mN, and the probe returned to its initial starting position at the unloading state at the end of each test. The indentation depth was recorded as a function of the normal force. The normal contact stiffness can be evaluated by calculating the slope of the initial portion of the unloading curve:

$$k_z = \frac{dF_z}{dz} \tag{1}$$

where z is the indentation depth and F_z is the normal load. The reduced elastic modulus E^* of the indented skin can be obtained from the slope of the initial portion of the unloading curve k_z of the load–displacement curve, as proposed by Oliver

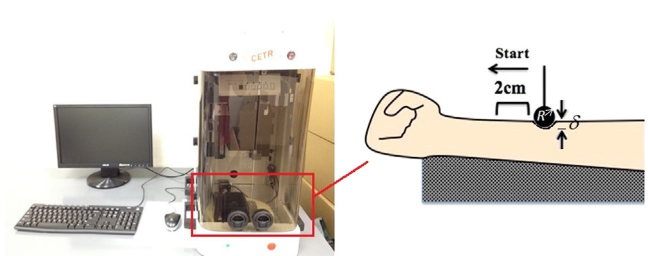

Fig. 1. UMT-2 tribology device setup (left), and test position of forearm skin (right).

and Pharr [26]:

$$E^* = \frac{\sqrt{\pi}}{2}\frac{k_z}{\sqrt{A}} \tag{2}$$

where A is the projected contact area. For a spherical indenter, the projected contact area is a function of indentation depth δ and probe radius R:

$$A = \pi\delta R \tag{3}$$

In the friction experiment, a spherical stainless steel ball with a diameter of 9.5 mm was used as the probe to rub against the tape-stripped dry inner forearm skin reciprocally. The human arm was supported by an adjustable holder and bound with a belt positioned at an appropriate distance (Fig. 1 right). In each experiment, the probe was pressed onto the forearm skin with a constant normal force from 0 to 0.196 N, moved on the forearm for 20 mm at a constant speed of 0.5 or 5 mm/s and then lifted off the skin. The measurement was repeated three times to acquire an average friction coefficient value. In this study, the contact radius a was smaller than the probe radius with $a/R<0.6$. That means, a/R is not sufficiently small compared with Hertz' assumption of $a/R \ll 1$. However, to study the elastic modulus of in vivo skin, Hertz equation was adopted by researchers to study trends.

2.4. UV/vis spectroscopic measurement

The pseudo-absorption of the stratum corneum on the stripped tapes was detected using UV/vis spectroscopy. The UV/vis spectroscopic measurement was carried out with a double-beam monochromic spectrophotometer (U-3010, Hitachi). The spectra were recorded from 200 to 500 nm. Clean tape was used as a baseline to avoid interference.

To quantify the amount of removed stratum corneum, the tape strips were fixed on sample holders, and their protein absorption [27] was measured. When stratum corneum aggregates, it decreases the transmission of light by reflection, diffraction and scattering. Protein absorption thus linearly increases with decreasing wavelength. The optical method can be used to measure the pseudo-absorption of the corneocytes in the visible range [8,27,28]. The value of the resulting absorbance was employed to measure the amount of stratum corneum removed by each tape strip. The resulting pseudo-absorption at 430 nm [29] is correlated to the weighing value [8,28] and the number of removed stratum corneum cell layers [30]. A UV/vis spectrometer was used to measure the absorption at 278 nm and pseudo-absorption at 430 nm. The stratum corneum mass removed by i consecutive tape strips was quantified as the following equation [8]:

$$m_i = \frac{A_{430}}{0.0048}\ (\mu g/cm^2) \tag{4}$$

where A_{430} is the absorbance measured at 430 nm. The cumulative thickness of the removed stratum corneum by n tape strips was calculated as

$$e_n = \left(\frac{1}{\rho_{sc} s}\right)\sum_{i=1}^{n} m_i \tag{5}$$

where m_i is the cumulative mass of stratum corneum removed by i consecutive tape strips, F is the area of a tape strip (5.7 cm^2), and ρ is the stratum corneum density, set to 1 g/cm^3 [31]. The frictional properties of the broken skin surfaces after tape stripping were discussed based on the amount and thickness of removed stratum corneum.

2.5. TEWL measurement

Trans-epidermal water loss was assessed by water evaporation through the Tewameter® TM 300 measures (Courage & Khazaka). This system has two temperature and humidity sensors in a hollow cylinder. The probe can measure the gradient of vapor pressure at different distances to the skin surface using pairs of sensors. During the TEWL measurements, air flowing was prevented by reducing movement in the test room. In order to prevent water loss, the probe was placed on skin without any pressing. The probe was measured until a stable TEWL value was established. Eventually, TEWL was calculated by Fick's law of diffusion.

3. Results

3.1. Changes in elastic modulus after tape stripping

To examine the layered structure of the skin, indentation test on forearm skin was carried out as a function of number of tape strips. Fig. 2 indicates that the caused skin deformation increased with increasing number of tape strips. The normal contact stiffness was also calculated from the slope of the initial portion of the unloading curve at the maximum normal load of 0.196 N (20 g), and the results are summarized into Fig. 3. It was shown that as the number of tape strips increases, the reduced elastic modulus gradually decreases. The initial

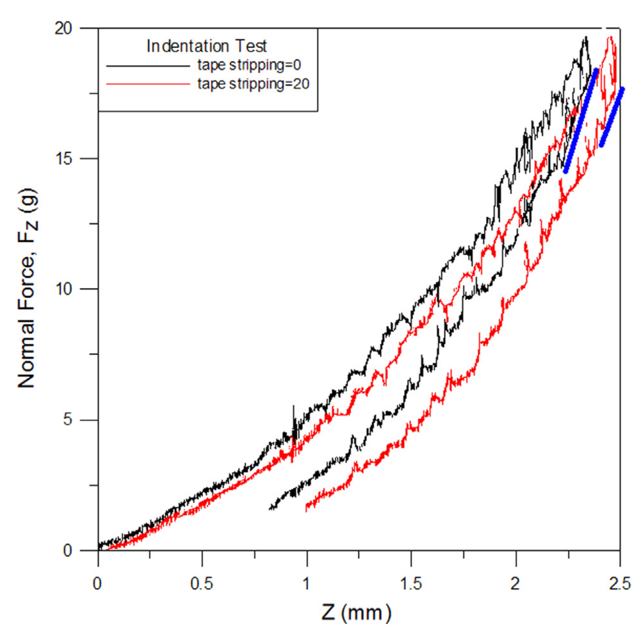

Fig. 2. Variation of normal force with caused skin deformation for various numbers of tape strips (representative).

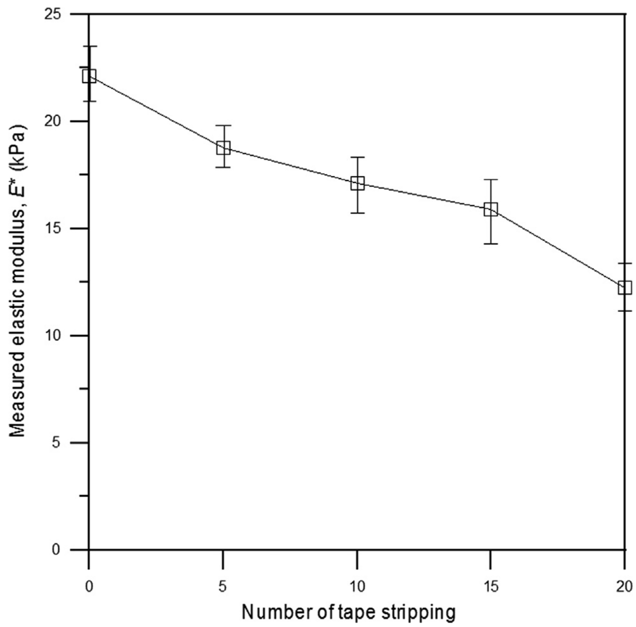

Fig. 3. Variation of measured elastic modulus with number of tape strips.

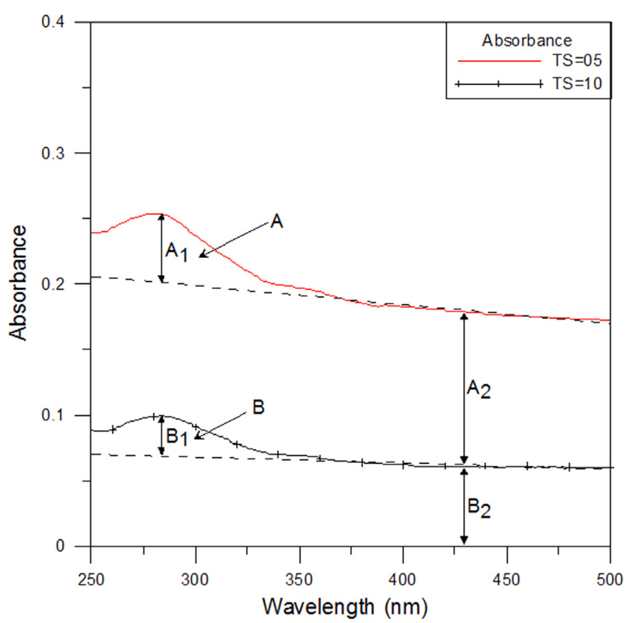

Fig. 4. UV/vis spectra of tape strips of forearm. (A) 5th strip; (B) 10th strip (representative).

elastic modulus of normal skin was 22.13 kPa and the value gradually reduced to 12.25 kPa after 20 times tape strip.

3.2. Effects of tape stripping on absorption of proteins and TEWL

Fig. 4 shows the UV/vis spectra of the 5th and 10th tape strips removed from the forearm skin. Both the pseudo-absorption and the protein absorption at 278 nm increased with increasing amount of removed stratum corneum. The absorption is given as

$$\frac{A_1}{A_2} = \frac{B_1}{B_2} \tag{6}$$

In Fig. 4, A_1 and B_1 represent the protein absorption on 5th and 10th stripped tapes, respectively. Fig. 5(a) and (b) shows the relationship between the absorbance at A_{430} and the weight of stratum corneum for each strip removed from the skin, respectively. The amount of stratum corneum removed by each tape strip decreased with increasing of number of tape strips. TEWL was applied to study the skin barrier function. Fig. 6 shows that the mean TEWL of the initial normal forearm skin is 9 g/m^2 h and increased up to 17.5 g/m^2 h after 20th tape strip. Therefore, TEWL increased with the amount of removed stratum corneum.

3.3. Changes in friction coefficient after tape stripping

The dynamic friction coefficient was calculated by averaging over 20 data points. The measured skin friction coefficient was averaged from three times of indentation and friction tests. Fig. 7 shows that the friction coefficient of skin increased with the number of tape strips. Notably, the friction coefficient increased greatly on the 20th tape strip. Fig. 7 also shows the influence of number of tape strips, sliding speed, and normal load on the friction coefficient. For a normal load of 0.196 N and a sliding velocity of 5.0 mm/s, the friction coefficients of initial normal skin, the 15th tape strip, and the 20th tape strip are 0.33, 0.56, and 0.87, respectively. However, for a normal load of 0.196 N and a sliding velocity of 0.5 mm/s, the friction coefficients of initial normal skin, the 15th strip, and the 20th strip decrease to only 0.22, 0.49, and 0.81, respectively.

3.4. Effect of increasing normal load on friction coefficient

During the friction test, the applied normal force was linearly increased from 0 to 0.98 N in 40 s at a sliding velocity of 0.5 mm/s. The measured friction force of the skin as a function of the normal load after different tape trip conditions is plotted in Fig. 8(a)–(e). It can be seen clearly that the slope of the curve-fitted line of the friction force versus the normal force increased with increasing number of tape strips. The fitted slope of initial normal skin is 0.26 and increased to 0.28 on the 5th tape strip. Finally, the fitted slope greatly increased to 0.86 after the 20th tape strip. Fig. 8(e) displays that when tape stripping times increase, friction coefficient is obviously divided into positive and negative slope sections for large normal loads.

4. Discussion

Figs. 2 and 3 reveal a reduced elastic modulus trend from the top to a lower layer of skin, indicating that skin has a gradient elastic modulus trend in the depth direction. Similarly, the structure of the stratum corneum has been found to be a composite [32]. Fig. 3 shows that the elastic modulus of skin

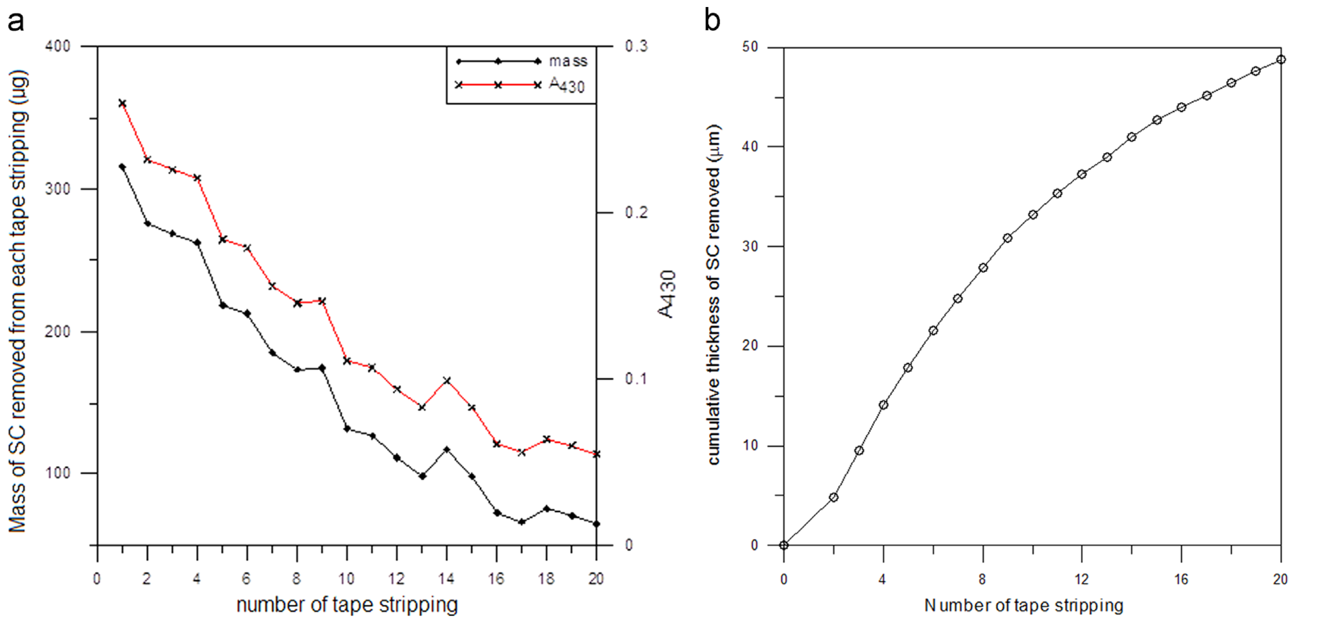

Fig. 5. (a) Average mass of stratum corneum removed from skin as evaluated using Eq. (4) and (b) average cumulative thickness of stratum corneum removed as calculated using Eq. (5).

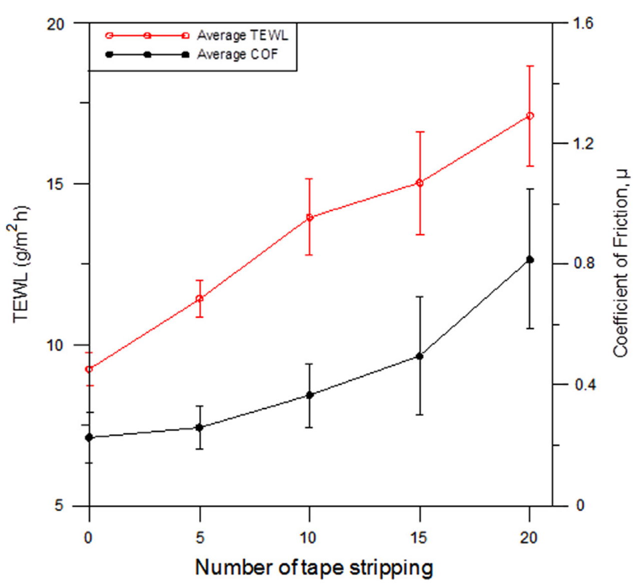

Fig. 6. Average TEWL value and average friction coefficient for various numbers of tape strips.

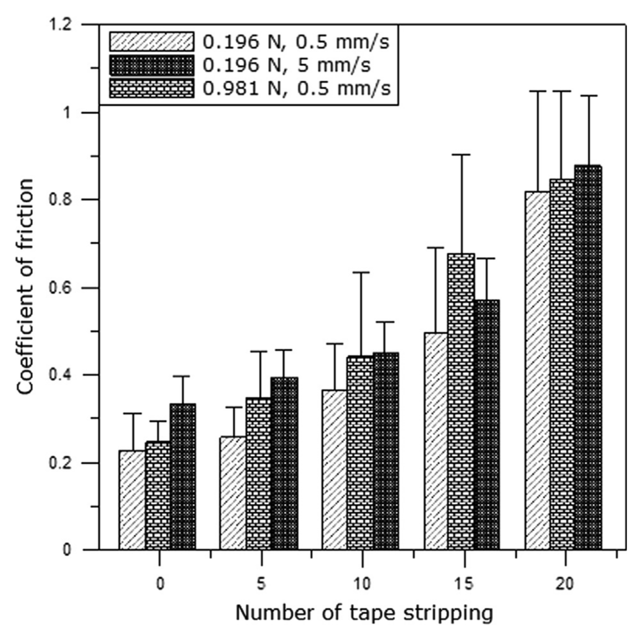

Fig. 7. Effects of normal load and probe sliding velocity on friction coefficient of skin for various numbers of tape strips.

decreased with increasing number of tape strips, indicating that the top stratum corneum layer is gradually removed from the soft skin. The decreased skin stiffness with increasing stratum corneum hydration (Fig. 6) can be attributed to the plasticization of the stratum corneum [19]. Comparing the obtained reduced elastic modulus with those in Ref. [33] indicates a good agreement for a probe diameter of 9.5 mm.

The protein absorbance at 278 nm can reflect the amount of stratum corneum removed by tape stripping, and it is proportional to the pseudo-absorption at 430 nm, as shown in Fig. 4. A_1 is larger than B_1 because the top-layer stratum corneum is thin and easier to be removed than the bottom stratum corneum layer, this is due to the intercellular bonding strength of the corneocytes is weak in the top stratum corneum layer. Fig. 5(a) shows the amount of removed stratum corneum decreased with the number of tape strips. These results also agreed with those in a previous work [32].

The water content is gradient inside the epidermis [34], which leads to different levels of moisture content. The skin barrier function can be observed by measuring TEWL after tape stripping. The measured TEWL was increased up to 17.5 g/m^2 h after 20th tape strips (Fig. 6) because tape stripping upset the water balance; as a consequence, tape

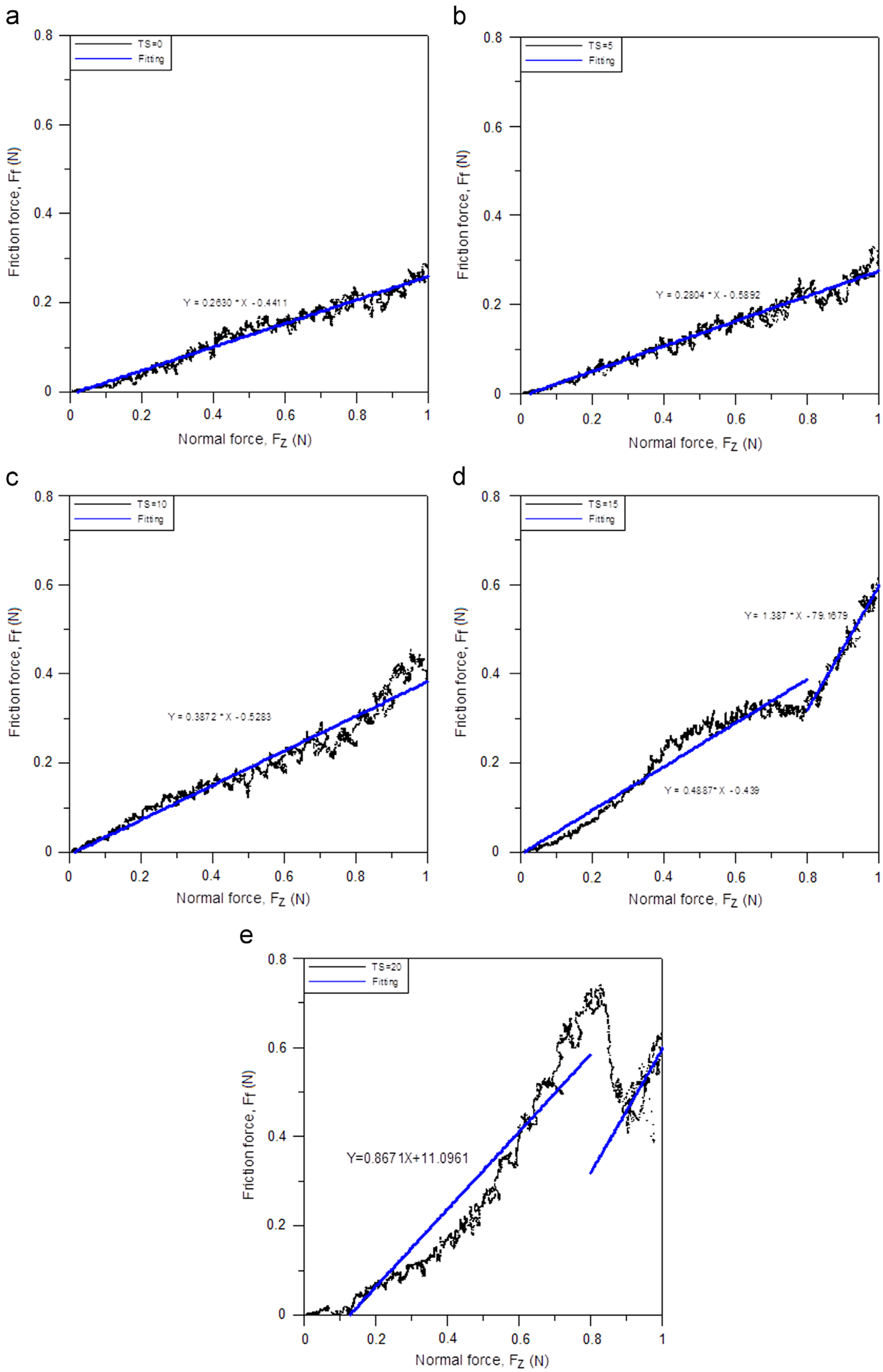

Fig. 8. Normal force and friction force (a) for initial normal skin, and after (b) 5, (c) 10, (d) 15 and (e) 20 tape strips (representative).

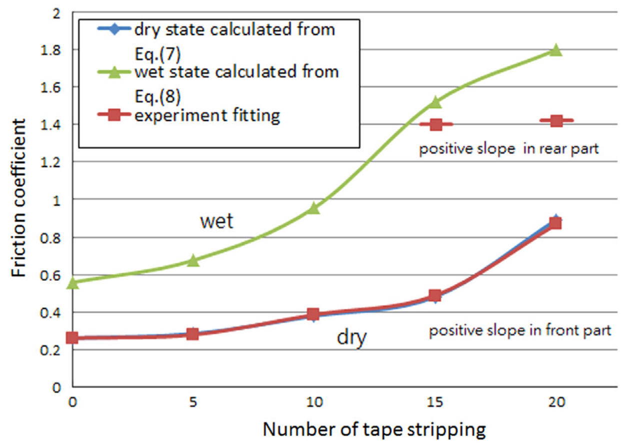

Fig. 9. Friction coefficient calculated from (a) Eq. (7), and (b) Eq. (8), and (c) fits of the experimental data in Fig. 8 (representative).

stripping made water to diffuse across the stratum corneum layer.

The friction of skin can be described as an adhesion mechanism determined by two factors [19], namely the surface energetics of the interfaces and the area of contact. The surface energetics on skin can be related to tissue fluid from deep skin [35]. A contact area of probe and flat human skin was larger than that of probe and rough skin surface. Therefore, to discuss the contact area of forearm skin, it is necessary to consider the tissue fluid and roughness of skin. The trends of the friction coefficient and the elasticity modulus for different stratum corneum layers are discussed below.

Fig. 8 shows the normal loads versus friction forces for various numbers of tape strips. Fig. 8(a)–(c) displays the coefficient of friction of skin is almost independent of the normal load, which is similar to Ref. [19] that the contact area of a rough skin surface is proportional to the normal load – because global mean asperity contact pressure remains constant. The friction coefficient in the dry state can be written as [36]

$$\mu = \frac{F_{adh}}{F_z} = \frac{\tau}{p} = \frac{\tau_0}{p} + \alpha = \frac{\tau_0 A}{W} + \alpha \tag{7}$$

with skin adhesion friction force F_{adh}, interfacial shear strength τ, the area of contact A, intrinsic interfacial shear strength τ_0, pressure coefficient α, and pressure p. When normal load increases, the slopes of Fig. 8(a)–(c) remain a positive constant, which are different to (e) composed of positive and negative slopes. Thus we conclude that contact surface on the forearm skin in Fig. 8(a)–(c) is topographically rougher and belongs to the dry state than that in (e). Furthermore, the friction coefficient increases with the number of tape stripes. Observing Fig. 3 displays that increasing tape stripping generates a soft skin surface, which supports the fact that skin surface is getting smooth from Fig. 8(a)–(e). Similarly, Adams et al. [19] revealed that a topographically smooth skin has a large friction coefficient. In addition, TEWL increases with the amount of removed SC as measured in Fig. 6, which enhances moisture of skin. Both the reduction in the elastic modulus and the increase of diffusing TEWL across the stratum corneum layer would result in a smoothing of wet skin contact [37–39]. Therefore, the friction coefficient gradually increases with increasing number of tape strips.

The slopes of friction–load curve in Fig. 8(e) can be divided into two positive regions and a minus region. From the Wolfram's adhesion model extended by Adams et al. [19], the friction coefficient of skin in the wet state can be expressed as

$$\mu = \frac{F_{adh}}{F_z} = \pi\tau_0 \left(\frac{3R}{4E}\right)^{2/3} W^{-1/3} + \alpha \tag{8}$$

with the shear strength τ_0, skin adhesion friction force F_{adh}, normal load F_z, probe radius R, effective elastic modulus E, and pressure coefficient α. That is, an increasing normal load decreases friction coefficient, as shown in a minus slope in Fig. 8(e). On 15th and 20th tape strips, firstly, as normal load increases, the frictional forces are proportional to normal loads. At this time, large normal loads benefits TEWL diffusion, and then moisture content gradually increases. Gradually, the skin surface transforms from the "dry" state to the "wet" state, in which asperities are flattened and results in a smooth contact. Then, an increasing normal load decreases friction force. Eventually, moving probes consistently removes the fluid on skin surface, and then reverts to a rough contact. This wetting/drying phenomena is supported by [19] that moisture plasticization results in a large reduction of the interfacial shear strength compared to the dry state. Fig. 9 shows the friction coefficient of various number of tape strips calculated from Eqs. (7) and (8) (ignoring the pressure dependence proposed by Wolfram [40]) and from fits of the experimental data in Fig. 8, respectively. There is agreement between these calculated values and experimental data. In addition, the friction coefficient indicates whether skin contact belongs to dry/wet state. Notably, negative slope region is not significant in Fig. 8(d). However, observing Fig. 9 indicates that the coefficient in the rear part of Fig. 8(d) is not large enough compared to those in wet state, because it is under a smooth contact but not in a full wet state. Moreover, increasing sliding speed enlarges friction coefficient. The friction coefficients increase slightly with increasing velocities due to velocity dependence of the interfacial shear stress τ. Thus, in both dry (Fig. 8(a)–(d)) and wet states (Fig. 8(e)), friction coefficients increase with the increasing sliding velocity.

As the probe indenting the skin and slides, the skin becomes smooth and hence increased the friction force increased with the number of tape strips. For a fixed normal load, the fluctuation in the magnitude are similar to the friction coefficient signals measured in [22] and may be attributed to the stick–slip phenomenon. The friction force built up with time, and slip occurs when the normal force exceeded the static friction force.

5. Conclusion

In vivo tribological experiments of forearm skin were carried out to study the influence of layered stratum corneum on skin elasticity and frictional properties. The effects of tape stripping on elasticity and the friction coefficient were investigated. The following conclusions were drawn:

1. The normal stiffness decreased but TEWL increased as a function of the amount of stratum corneum removed.
2. On 20th tape strip, the friction experiments shows the dry/wet state changing, and then contact skin surface topographically changes from rough to smooth, which affects skin frictional behavior. The removal of stratum corneum flattened the skin and enhanced the stick–slip phenomenon.

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